López, G., Moreno, J.I., Amarís, H. y Salazar, F. (2015). Paving the road toward Smart Grids through large-scale advanced metering infrastructures. *Electric Power Systems Research*, 120, pp. 194-205.

DOI: https://doi.org/10.1016/j.epsr.2014.05.006

Paving the road toward Smart Grids through large-scale advanced metering infrastructures

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a b s t r a c t

Upgrading current electricity grid to the so-called Smart Grid represents one of the major engineering challenges ever. Hence, the road toward the Smart Grid will be long and needs to be paved gradually, certainly driving the next wave of research and innovation in both the energy and the ICT (Information and Communications Technologies) sectors. Currently, the earliest stages of such a complex project are being undertaken and AMI (Advanced Metering Infrastructures) stand out as the first steps toward the Smart Grid. The Spanish R&D (Research and Development) demonstration project PRICE-GEN aims to be a flagship AMI project at both national and international level. It is focused on increasing the awareness of the status of the low voltage power distribution network through an optimal and interoperable communications architecture which provides detailed information on customers' consumption and generation. The project entails the deployment of over 200,000 smart meters in the area of Madrid, such a pilot scheme being also used as reference in other European R&D projects, such as the IGREENGrid (IntegratinG Renewables in the European Electricity Grid). This paper presents the communications architecture and technologies which are deployed in the field, analyzing how they fit some specific Smart Grid communications requirement. In addition, the paper describes in detail the pilot itself along with the services which are currently been delivered as well as with the foreseen ones. Finally, the main trends in AMI from the ICT perspective are also discussed.

Keywords:
Advanced Metering Infrastructure (AMI) Distribution
Management System (DMS) Information and
Communications Technologies (ICT)
Machine-to-Machine (M2M) Communications
PoweRline Intelligent Metering Evolution (PRIME)
Smart Grid

1. Introduction

The so-called Smart Grids can be defined as electrical grids that take advantage of ICT (Information and Communication Technologies) to coordinate the necessities and capabilities of all their stakeholders with the aim of supplying power in a cost-effective and sustainable manner and providing high levels of quality and security [1].

Although the Smart Grid concept can be summarized in a paragraph, putting it in practice represents one of the most challenging engineering projects ever, as long as it means a revolution at every domain of such a complex and critical system as the electrical grid.

This revolution basically aims at converting a highly centralized and static system, where few energy generators supply electricity to a huge number of consumption points without real-time information exchange between them [2], into a highly distributed and dynamic system, where there are more energy generators, of lower capacity and geographically distributed, which are able to communicate with the consumption points in order to coordinate and optimize their operation [3,4].

Therefore, the transition from the traditional electrical grid to the Smart Grid needs to be gradual. This evolution can be divided into three stages or generations [5]. The first stage (so-called Smart Grid 1.0) is focused on the monitoring and control of consumption, involving technologies and applications such as EMS (Energy Management Systems), AMI (Advanced Metering Infrastructures), or DR (Demand Response). Once this is operational, the electrical grid will be ready to accommodate DG (Distributed Generation). Thus, the second stage (so-called Smart Grid 2.0) deals with elements such as energy storage, which is crucial to match consumption and gen-eration, or EVs (Electric Vehicles), taking advantage of their triple role as consumer, generator, and energy storage equipment. Finally, the third stage (so-called Smart Grid 3.0) is foreseen to be focused on operational issues, such as a dynamic and P2P (Peer-to-Peer) electricity market.

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ABDP	Accumulated Bandwidth-Distance Product
AES	Advanced Encryption Standard
AES-CBC	Advanced Encryption Standard – Cipher Block Chaining
AMI	Advanced Metering Infrastructure
AP	Aggregation Point
ARQ	Automatic Repeat Request
BPL	Broadband Power Line Communications
CBA	Cost Benefit Analysis
CDMA	Code Division Multiple Access
CFP	Contention-Free Period
CNTR	Concentrators
COSEM	Companion Specification for Energy Metering
CPCS	Common Part Convergence Sublayer
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
DG	Distributed Generation
DLMS	Device Language Message Specification
DMS	Distribution Management System
DR	Demand Response
DSO	Distribution System Operator
EC	European Commission
EEGI	European Electricity Grid Initiative
EMS	Energy Management Systems
EU	European Union
EV	Electric Vehicle
E2E	End-to-End
FAN	Field Area Network
FTP	File Transfer Protocol
GPRS	General Packet Radio Service
GW	Gateway
ICT	Information and Communications Technologies
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineering
IGREENGrid	IntegratinG Renewables in the European Electricity Grid
IP	Internet Protocol
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
LTE	Long Term Evolution
LV	Low Voltage
MAC	Medium Access Control
MDMS	Meter Data Management System
MPLS	MultiProtocol Label Switching
MV	Medium Voltage
M2M	Machine-to-Machine
NAN	Neighborhood Area Network
NB-PLC	Narrowband – Power Line Communications
OFDM	Orthogonal Frequency-Division Multiplexing
OSGP	Open Smart Grid Protocol
PDU	Protocol Data Unit
PHY	PHYsical
PLC	Power Line Communications
PRICE	Joint Project of Intelligent Networks in the Henares Corridor
PRIME	PoweRline Intelligent Metering Evolution
P2P	Peer-to-Peer
QoS	Quality of Service
RAN	Radio Access Network
R&D	Research and Development
SCP	Shared-Contention Period
SDU	Service Data Unit
SIM	Subscriber Identity Module
SS	Secondary Substation
SSCS	Service Specific Convergence Sublayer
TC	Transformation Center
TCP	Transport Control Protocol
TSO	Transmission System Operators
UK	United Kingdom
USA	United States of America
VPN	Virtual Private Networks
V2G	Vehicle-To-Grid
WAN	Wide Area Network
WiMAX	Worldwide Interoperability for Microwave Access
XML	eXtensible Markup Language

Currently, the electric power industry is facing the earliest stages of this metamorphosis, where AMI stand out as the first steps toward the Smart Grid. AMI deployments are mainly driven by regulation (e.g., directives 2009/72/EC and 2009/73/EC, at European level, or directive IET/290/2012, at Spanish level). However, this push meets an actual requirement, since increasing the awareness of the distribution power network is crucial to enable more sophisticated mechanisms, such as DR [6] or proper EV massive integration through V2G (Vehicle-To-Grid) [7].

AMI allow bidirectional communications between the smart meters and the information system, for why smart meters are not just sensors any longer, but they become part of the core of the power distribution network itself. AMI bring benefits both to the operators or utilities and to the customers. On the one side, AMI make the operation and maintenance of the power distribution net-work easier, allowing, e.g., enabling or disabling meters, updating them, or retrieving their data (either periodically or on demand) remotely. On the other side, thank to AMI, customers will be pro-vided with enriched information about their consumption (e.g., hourly consumption curves, which can be used to change consump-tion habits or to properly select the maximum contracted power in order to reduce the electricity bill), and can take advantage of new services, such as differentiated pricing.

M2M (Machine-to-Machine) communications, which allow networked devices to communicate among themselves without further human intervention, play a key role in the Smart Grid, in general, and in AMI, in particular, in that they enable the bidirectional real-time exchange of information between the consumption and generation facilities to be monitored and controlled, and the information systems where the optimization processes run.

The Spanish R&D (Research and Development) project PRICE-GEN [8] aims to be a flagship AMI project at both national and international level.[1] The main goals of this project are:

- Design an optimal and interoperable M2M communications architecture.
- Develop novel and smart sensing and actuating equipment, which provide information on consumption and generation that allows having a more accurate picture of LV (Low Voltage) power distribution networks in almost real-time.
- Validate this platform by means of a pilot scheme which entails the deployment of over 200,000 smart meters and their integration into the operational power distribution infrastructure of a geographical area close to Madrid (Spain).

[1] As a matter of fact, the PRICE project has been awarded with the EEGI (European Electricity Grid Initiative) CORE LABEL, which is the highest price given by this initiative and proves that the project is fully aligned with the criteria and objectives of the EEGI.

This paper is mainly focused on the M2M communications architecture and technologies which are deployed in the aforementioned pilot scheme, as well as on the details of its current and foreseen operation.

The remainder of the paper is structured as follows. Section 2 briefly outlines some relevant requirements that Smart Grid communications must meet. Section 3 presents the designed M2M communications architecture and selected technologies, analyzing how they fit such specific Smart Grid communications requirements. Section 4 describes the pilot scheme itself, paying special attention to how it is currently operated (e.g., test that are carried out, services that are delivered) and to the next steps. Section 5 presents two relevant expected outcomes of the project, namely a guide for optimal design of M2M communications infrastruc-tures for AMI and a state estimator tool for LV power distribution networks. Section 6 discusses the related work and current technological trends in AMI from the ICT perspective. Finally, Section 7 summarizes the paper and draws conclusions.

2. Communications requirements

Communications for the Smart Grid present specific requirements from both the technical and economic perspectives, such as [9–14]:

- *QoS (Quality of service)*: The communications infrastructure must provide a given level of QoS that fits the target application. Notably, QoS policies are mainly oriented to traffic prioritization and resource allocation to face congestion situations. Some parameters which are widely used to quantify such a QoS level are:
  - *Latency*: It can be defined as the E2E (End-to-End) delay of the data. Latency represents a key parameter in applications of protection and control in substations, in which it must be guaranteed that it is lower than a given value (typically, 4 ms). However, in current AMI applications for the residential sector, latency constraints are more relaxed.
  - *Bandwidth*: The communications infrastructure must provide an aggregated data rate as high as to carry the traffic associated to the target application. In general, this will depend on the volume of devices as well as on the size of the exchanged packets and the traffic pattern.
  - *Reliability*: The communications infrastructure must guarantee that it will work correctly during a given percentage of time throughout a year. The more critical the application is, the higher such a percentage will be.
- *Interoperability*: The communications infrastructure must allow equipment from different manufacturers to interact seamlessly. In order to achieve this goal, the main functional blocks which compose the communications infrastructure as well as the interfaces among them must be defined and standardized. As a matter of fact, standardization is crucial to effectively achieve this goal, which eventually fosters competition and thus yields more reliable products at lower cost.
- *Scalability*: The communications infrastructure must ensure scalability from both the technical and economic perspectives. First, taking into account the huge number of devices this kind of systems involves, the selected communications technologies must minimize the deployment, maintenance, and operational costs. Second, the communications architecture must be able to incorporate new devices and to accommodate new services.
- *Security and privacy*: Due to the fact that Smart Grid applications handle sensitive data, security (both physical and cyber-security) and privacy represent key factors for their wide adoption. If privacy is not guaranteed, many users will not embrace many of the new services. If security is not guaranteed, many service providers will not implement or rely on many of such new services. However, since these two features and cost are usually directly proportional, a trade-off is required in order to obtain feasible solutions.

3. Communications network architecture

Fig. 1 shows an overview of the M2M communications architecture designed under the scope of the PRICE-GEN project in order to meet the requirements outlined in Section 2, as well as the most common power network typologies of this kind of deploy-ments (i.e., urban, semi-urban, and rural). As it can be seen, it is a heterogeneous network architecture in that it comprises three different network configurations (labeled as (1), (2), and (3) in Fig. 1), each of them being composed of different network segments where multiple communications technologies are used.

Such configurations have to do with how smart meters communicate with the MDMS (Meter Data Management System), i.e.:

1. Through Concentrator
2. Through Concentrator and Gateway
3. Directly

The Communication through Concentrator represents the basic configuration of the PRICE-GEN project. It is specially designed for urban or semi-urban scenarios with a LV network of medium to high quality.[2] It is a 2-level hierarchical architecture which makes the most out of the power distribution infrastructure itself with the aim of speeding deployments up and boosting scalability.

Fig. 2 shows how this communications network configuration is mapped onto the LV power distribution infrastructure. As it can be seen, smart meters are associated to customers; whereas the so-called CNTRs (Concentrators) are located in the TCs (Transformation Centers), also known as SSs (Secondary Substations). Customers and TCs are electrically connected through LV cables.

A TC of the considered power distribution networks can be equipped with one, two, or three transformers, which are responsible for adapting MV (Medium Voltage) to LV. Each transformer manages typically four LV lines. Smart meters are connected to such LV lines in a bus topology.

To be more precise, within the TC itself, the CNTRs are associated to the transformers. If there are more than one CNTR within the same TC, one will work as master; whereas the remainder CNTRs will work as slave from the communications perspective. The communications between master and slaves typically rely on Ethernet.

From the AMI perspective, the main goal of the CNTR is to aggregate the traffic coming from the smart meters, thus boosting scalability. The master CNTR is responsible for managing the communications with the MDMS, which is not associated to any specific element of the power distribution grid, but it is typically located in the data center of the DSO (Distribution System Operator).

The Communication through Concentrator and Gateway is a 3-level hierarchical configuration which fits the hierarchy of the power distribution network itself with the aim of making the most out of the power infrastructure as communications medium. Thus, smart meters are associated to customers, CNTRs are associated to TCs, and the so-called GWs (Gateways) are associated to primary

[2] It should be noted that in this paper the quality of the power networks is evaluated from the communications perspective. Thus, high quality power networks refer to power networks where cables present high conductivity, low noise, and short length; whereas low quality power networks refer to power networks where cables present low conductivity, high noise, and long length.

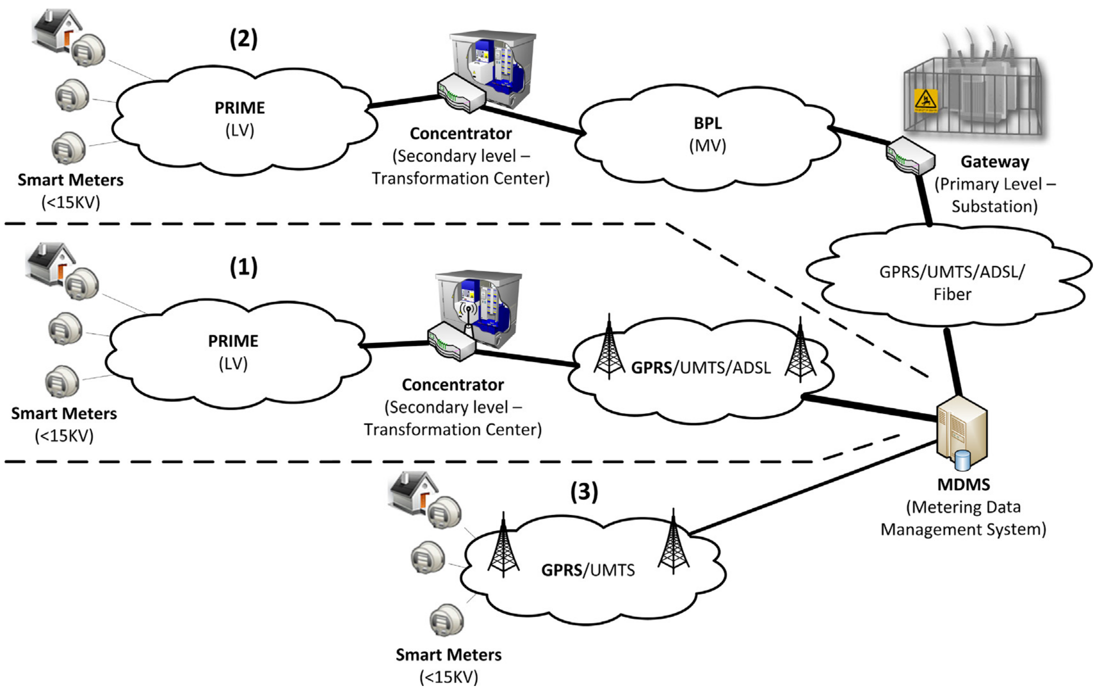

Fig. 1. Overview of the M2M network architecture deployed and operated in the PRICE-GEN project.

substations. TCs and primary substations are electrically connected through MV cables. Hence, this configuration uses both the LV and the MV infrastructure as communications media.

Finally, the Direct Communication is specially recommended for very specific situations, such as rural scenarios where either there are few smart meters or the quality of the LV network is very low or both. This configuration comprises a single network segment, which compromises scalability, although in such very specific sce-narios this is not a critical parameter.

Next subsections elaborate on these communications network configurations paying special attention to the protocol stack and communications technologies, and to how they meet the require-ments outlined in Section 2.

3.1. Communication through Concentrator

Fig. 3 shows the communications technologies and protocol stack in use in this communications network configuration. Fig. 3 also maps it onto the standard reference architecture defined in [15].

As it can be seen, the communications between smart meters and the MDMS are based on PRIME (PoweRline Intelligent Metering Evolution) [16]. PRIME is a second-generation NB-PLC (Narrow-band – Power Line Communications) solution which uses the LV cables as communications media, thus reducing the deployment costs of this network segment.

PRIME provides data rates up to 130 Kbps, which seem to be fair enough for AMI applications. The reliability and availability of this technology is tightly related to the quality of the LV cables, which affect the quality of the communications. In this regard, the most relevant problems have to do with noise and attenua-tion [17,18]. This is the reason why this configuration is specially recommended for LV networks of medium to high quality from the communications perspective with the aim of maximizing reliability and availability.

PRIME specification is open and free, which allows any company to manufacture PRIME-compliant devices, thus fostering interoper-ability considerably. As a matter of fact, interoperability tests have been carried out in field with successful results [19]. In addition, the PRIME protocol stack supports security at different layers [16].

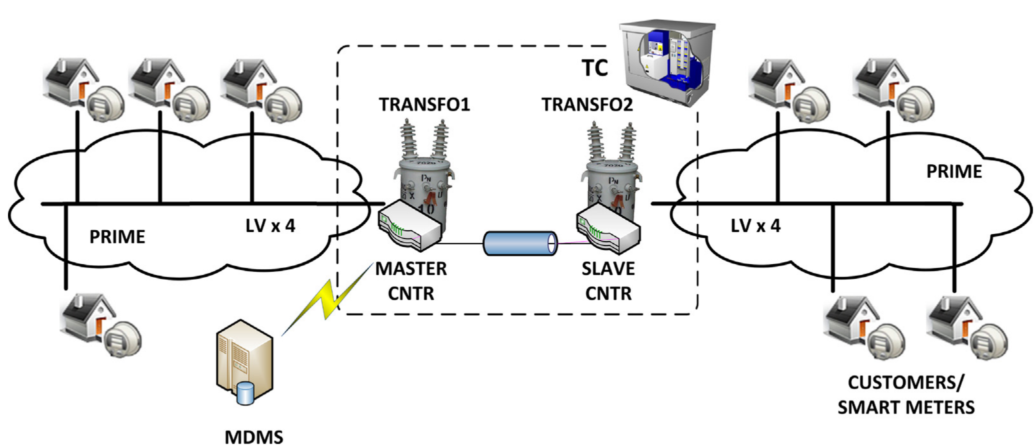

Fig. 2. Mapping of the communications infrastructure onto the electricity distribution infrastructure for the specific case of Communications through Concentrator.

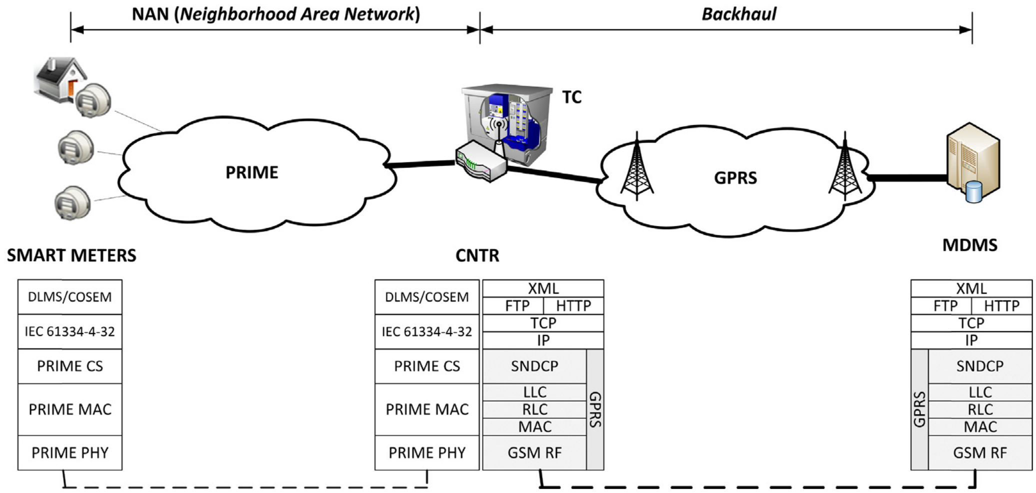

Fig. 3. Communications technologies and protocol stack for the specific case of Communications through Concentrator.

PRIME specification deals with the PHY (PHYsical) layer, the MAC (Medium Access Control) layer, and the convergence layer. At the PHY layer, it is worthwhile to remark upon that it uses OFDM (Orthogonal Frequency-Division Multiplexing) as modulation and that it works within the CENELEC-A frequency band (to be more precise, between the 41 KHz and the 89 KHz). At the MAC layer, two types of nodes are defined: the base nodes and the service nodes. The base nodes are the CNTRs in our case. The service nodes can work either only as meters or as both meters and switches. The switches are kind of communications repeaters that aim at mitigat-ing the effects of attenuation and noise, thus increasing the range and improving performance. These nodes can access the channel during the SCP (Shared-Contention Period) or request a transmis-sion slot during the CFP (Contention-Free Period). During the SCP, CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) is used as MAC technique. Table 1 summarizes the main features of the PHY and MAC layers of PRIME [20].

The convergence layer is further divided into:

- CPCS (Common Part Convergence Sublayer), which is responsible for fragmenting and assembling the PDU (Protocol Data Unit) of the upper layers to adapt it to the SDU (Service Data Unit) of the MAC layer.
- SSCS (Service Specific Convergence Sublayer), which allows managing several upper-layer protocols. In this regard, PRIME supports IPv4, IPv6, and IEC61334-4-32.

Table 1
Summary of PRIME PHY and MAC layers.

Layer	Feature	PRIME
PHY	Modulation	OFDM
	Frequency band	CENELEC-A (41–89 KHz)
	Data rate	Up to 130 Kbps
MAC	Topology	Tree (using switches)
	Network formation	Beacon discovery, automatic promotion
	Multi-hop routing	Yes
	Keep-alive monitoring	Yes
	Connection management	Yes
	Medium access	CSMA/CA
	ARQ (automatic repeat request)	Selective ARQ E2E
	Security	128-AES in CBC
	Aggregation	Optional in switch node

At the application layer, DLMS/COSEM (Device Language Message Specification/Companion Specification for Energy Metering) is used. To be more precise, COSEM (IEC 62056-61/62) is a profile of the application protocol DLMS (IEC 62056-53) tailored to energy metering [21,22]. DLMS/COSEM comprises a data model to represent the typical data associated to smart energy meters along with a communications mechanism based on messages to exchange such data. DLMS/COSEM provides some security features, mainly related to: (1) access control; (2) event registry; and (3) message ciphering [23].

The communications between the CNTRs and the MDMS are based on cellular networks (mainly, GPRS – General Packet Radio Service). GPRS is a mature and widely deployed technology throughout Europe, which speeds deployments up while also ensuring interoperability.

GPRS provides data rates up to 110 Kbps, in the downlink, and up to 26.8 Kbps, in the uplink [24]. The GPRS network is operated by a third party (the so-called network operator), so the deployment costs are limited to purchasing SIM (Subscriber Identity Module) cards and there is no maintenance cost.

Since the CNTRs aggregate the data coming from the smart meters, the volume of traffic that is carried by the GPRS network is reduced. This boosts scalability from both technical (allowing adapting PRIME to GPRS) and economical perspective (reducing operational costs).

In order to maximize the availability of this network segment, CNTRs are connected to the MDMS through several network operators (typically two, in the considered deployment). The historical data with two network operators measured in the field show an availability of 97.07%.

Regarding security, GPRS supports robust security mechanisms. In addition to them, VPN (Virtual Private Networks) are established between the CNTRs and the MDMS [25].

At the upper layers, the communication between the CNTRs and the MDMS is based on Web Services on top of FTP/TCP (File Transfer Protocol/Transport Control Protocol). Both data and commands are coded in XML (eXtensible Markup Language).

Currently, the backup of the smart meters' data from the CNTRs to the MDMS is done once a day, which illustrates that the delay does not represent such a critical parameter in AMI applications nowadays. However, if the gathered data were input to other applications such as DR, the backup periodicity could be reduced down to the sending periodicity of the smart meters. Likewise, remote actions on the smart meters (e.g., disabling, enabling, power changes) are currently being performed in real-time.

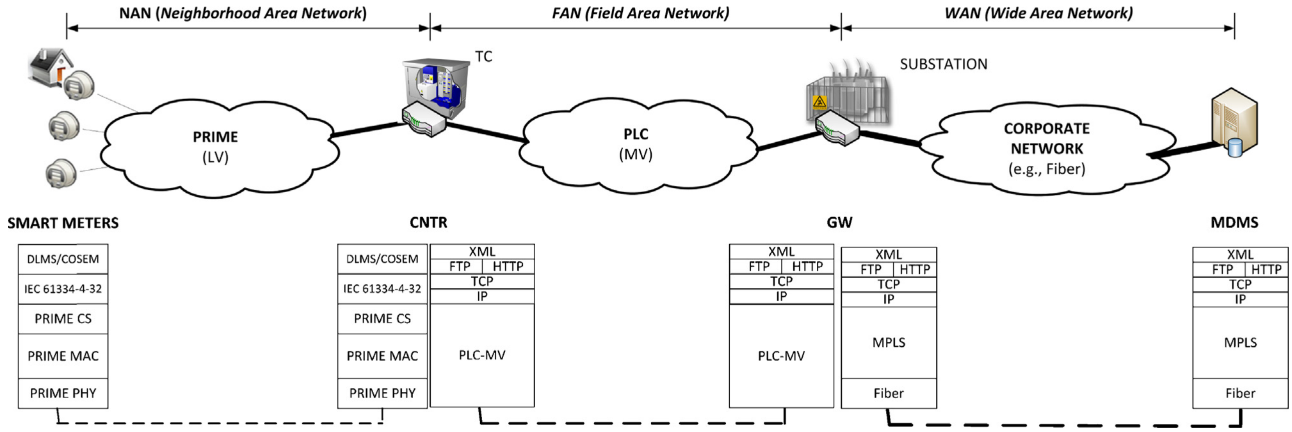

Fig. 4. Communications technologies and protocol stack for the specific case of Communications through Concentrator and Gateway.

3.2. Communication through Concentrator and Gateway

Fig. 4 shows the communications technologies and protocol stack in use in this communications network configuration, highlighting the mapping onto the standard reference architecture defined in [15].

In this configuration, the smart meters keep communicating with the CNTRs using PRIME and the communication between CNTRs and GW is based on BPL over MV [26–28]. Therefore, it is specially recommended for LV and MV networks of medium to high quality from the communications perspectives.

The communications between the GW (also known as Back-End, in IEEE, 1901 terminology [26]) and the MDMS depend on the com-munications technology the GW is equipped with.[3] If the primary substation where the GW is located were connected to the cor-porate network of the DSO, this kind of networks often relies on MPLS (MultiProtocol Label Switching), which is a 2.5 layer proto-col that supports traffic engineering, QoS, and VPN, thus allowing associating a specific label to the AMI traffic in order to handle it appropriately.

This configuration present very low deployment costs, since it makes the most out of the power distribution infrastructure itself as communications medium. The operational costs are lower than in the configuration presented in Section 3.1, since in this case the DSO does not have to pay a third party based on the volume of data carried by the cellular network. However, maintenance costs (which could be also considered within the operational costs) are higher, since the DSO is responsible for fixing any fault in the MV network.

Regarding availability, as it has already been mentioned, it will depend on the quality of the MV network from the communications perspective. In this regard, in-field tests and the simulations out-lined in Section 5.1 are crucial to determine under which conditions of the MV network communications performance is unacceptable, so the configuration presented in Section 3.1 should be deployed instead.

3.3. Direct communication

Fig. 5 shows the communications technologies and protocol stack in use in this communications network configuration, highlighting the mapping onto the standard reference architecture defined in [15].

[3] As a matter of fact, this is typically the main criterion considered to select the most appropriate substation to work as GW between all the substations belonging to the same BPL cell.

As it has already been said, within the scope of the PRICE-GEN project, this configuration is considered a solution for very extraordinary situations, since it presents several drawbacks:

- As it can be seen in Fig. 5, this solution would in principle imply that the MDMS is able to process DLMS/COSEM messages. However, although these three configurations co-exist in the PRICE-GEN pilot scheme, in particular, and in any AMI deployment, in general, ideally data handling should be performed in a uniform manner regardless of how and where they come from [29]. Nevertheless, Virtual CNTRs (Fig. 5) are implemented at the back-end in order to avoid this kind of problems.
- Deployment costs increase considerably in that the number of SIM cards is around two orders of magnitude higher, since the typical number of smart meters per CNTR is in the order of hundreds and in this configuration every smart meter needs to be equipped with a SIM card; whereas in Section 3.1 only CNTRs need to be equipped with SIM cards.
- The volume of data carried by the GPRS network increases since aggregation is not performed. As a result, operational costs also increase.

3.4. Summary

Table 2 summarizes qualitatively how the different communications network configurations presented throughout this section meets the requirements outlined in Section 2.

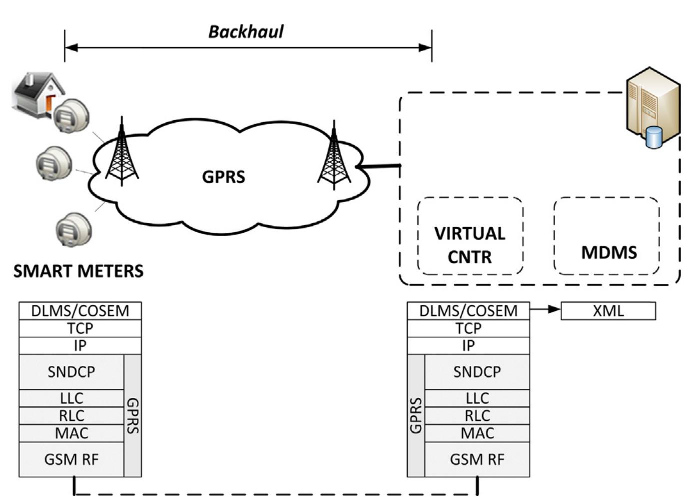

Fig. 5. Communications technologies and protocol stack for the specific case of Direct Communications.

Table 2
Summary and qualitative comparison of the main communications network configurations deployed and operated in the PRICE-GEN pilot.

Comms techs	1. Through CNTR *NAN*: PRIME*Backhaul*: Cellular	2. Through CNTR and GW *NAN*: PRIME*FAN*: BPL*WAN*: Corporate network	3. Direct *Backhaul*: Cellular
Reliability	√√√	√√	√√
Interoperability	√√√	√√	√√
Deployment costs	€€	€	€€€€
Operational costs	€€	€	€€€€
Maintenance costs	€	€€	€
Scalability	√√√	√√√	√
Security	√√√	√√√	√√ (No VPN)

€, Lowest cost; €€€€, Highest cost.

4. Pilot description

The PRICE-GEN pilot is deployed in the North-East of Madrid (Spain), specifically in the Henares corridor, covering a wide area that includes five towns:

- Guadalajara: 83,000 inhabitants
- Alcalá de Henares: 204,000 inhabitants
- Torrejón de Ardoz: 118,000 inhabitants
- Meco: 12,500 inhabitants
- Azuqueca de Henares: 30,000 inhabitants

The distribution power network of the PRICE-GEN pilot scheme operated by Gas Natural Fenosa supplies a total of 63,554 customers, including 3 primary substations, 44 MV lines, 583 SSs with a total installed power of 318,429 kVA, and the 63,554 smart meters associated to the already mentioned customers.

For the automation of secondary and primary substations, solutions based on current state-of-the-art real time communications standards (e.g., IEC61850) are used in the PRICE-GEN pilot scheme, since latency represents a critical parameter in this kind of applications, having to be deterministic and lower than a maximum acceptable value. However, this is out of the scope of the PRICE-GEN project itself, which is focused on the LV power distribution network up to the SSs, where the smart meters' data are aggregated. As it has been presented in Section 3, the MV power distribution network is used as an alternative communications segment to communicate such SSs with the MDMS.

The typology of the LV network under test is heterogeneous. There are rural, semi-rural and urban lines. To be more precise, there are 100.52 km of overhead lines, and 220.3 km of underground cables. The average value of SSs per primary substations is 194. In urban scenarios, the average length of the line between SSs is 0.34 km, the average value of meters per SS is 133, and the average installed power per SS is 606 kVA.

The communications network configuration deployed in the pilot depends indeed on the typology of the LV network. The communications network configuration presented in Section 3.1 (i.e., Communications through Concentrator) is the most widely deployed one. BPL over MV (i.e., Communications through Concentrator and Gateway) is being also tested at smaller scale. This option represents a very promising option for DSOs, but CBA (Cost Benefit Analysis) including technical and economic factors need to be car-ried out in practice to decide between this configuration and the configuration presented in Section 3.1, so such tests aim to shed light on this issue. Finally, as it has already been said, the Direct Communications based on cellular technologies is a very extraordi-nary solution which is deployed mainly in rural areas where either there are few smart meters or the quality of the LV network is very low from the communications perspective or both.

The data gathered by the smart meters are filtered and processed at the MDMS. The resultant information is shared and managed by customers using web-access, through the so-called Consumer Portal, where they can consult their processed hourly consumption curves, including hourly electricity prices and monthly bills, and receive recommendations to improve their behaviors and habits from the energy point of view.

Current operation of the pilot includes:

- Validation of the M2M communications architecture presented in Section 3 in a real environment with more than one hundred thousand meters.
- Analysis and determination of technical and non-technical losses, balancing the data from measuring equipment in the secondary substations and from customers' smart meters.
- Validation of the equipment by means of tests under network contingencies.
- Designing of energy management tools for Smart Grids.
- Enabling/disabling smart meters remotely.

The following items are foreseen in the near future:

- Analysis of dynamic behavior of power electronic devices, as well as smart metering, and supervision and automation equipment.
- Analysis of power flow variations due to project deployment.
- Studies on power signal quality and event detection.
- Determination of the most promising protocols at application level that better adapts to functional and operational requirements, and evaluation of them in a real environment.
- Design of a web tool to visualize the network status (supervision and control).

5. Advanced services

5.1. Guidelines to optimally design communications infrastructures for AMI

Network simulations are planned to be carried out under the PRICE-GEN project in order to evaluate the M2M communications architecture presented in Section 3 in scenarios and situations which are out of the scope of the deployed pilot scheme. The main outcome of such network simulations will be to obtain design criteria that are valid to be taken into account as guidelines for future larger-scale deployments.

These network simulations will be approached following the same methodology presented in [30]. Thus, actual data from the power distribution infrastructure of the deployed pilot scheme are taken as reference. In addition, the network segment comprising smart meters and CNTRs and the network segment comprising CNTRs and GW are addressed and evaluated separately. Reference [31] is taken as baseline to model the PRIME channel; whereas [26–28] are taken as basic reference, and [32–37] are also considered of interest, for the evaluation of BPL over MV in the specific scenarios of the PRICE-GEN project.

5.2. Increasing the awareness of the distribution power network state

One of the major challenges in Smart Grids is to have full knowledge of the distribution power network. This is crucial to allow matching consumption and generation, thus ensuring system stability. Beside this, it can further enable advanced services such as fraud detection.

The aforementioned objective can be obtained by means of state estimation. State estimation has been traditionally used by TSOs (Transmission System Operators) in transmission power networks [38–40]. The process is usually performed using extensively redundant data and it is based on a complete knowledge of the transmission power network.

In distribution networks, the situation is completely different. In many cases, there is a great uncertainty about the distribution network parameters, since measurements are scarce. Consequently, state estimation algorithms used in transmission power networks are not adequate to be used in distribution power networks.

5.2.1. State estimation algorithm

The proposed state estimation algorithm performs the following activities:

1. Data acquisition from smart meters. The selection of measurements is a crucial decision in order to obtain complete observability of the power network based on minimum number of measurements. In this project, the available real-time data are collected by the deployed smart meters and correspond to actual measurements of active and reactive energy consumed or delivered by each client connected to the network.
2. Topology and network parameter estimation. Generally speaking, distribution networks are radial with multiple short branches which present very low impedance (mainly resistive) [41]. This fact can lead to numerical convergence problems in the algorithms.
3. Observability analysis. This analysis is critical, because there is a lack of redundancy in the measurements which lead to highly unobservable distribution networks [42].
4. State vector estimation. Weighted least square algorithm can be solved by using Lagrange multipliers [43]. In this case, the optimization problem to be solved can be found minimizing the Lagrange function $\mathcal{L}$:

$$\mathcal{L} = \frac{1}{2}[Z - h(x)]^T R^{-1}[Z - h(x)] + \lambda^T g(x) \qquad (1)$$

where x is the state vector; λ is the Lagrange multiplier; Z is the measurement vector; $h(x)$ is the matrix between measurements and state variables; R is the variance matrix associated to measurements; $g(x)$ represents the pseudo-measurements which correspond to the unobservable region (i.e., estimation of load if smart meters are not available).

The state vector can be obtained by minimizing the Lagrange multiplier applying (2):

$$\frac{\partial \mathcal{L}(x, \lambda)}{\partial (x)} = -H^T R^{-1}[Z - h(x)] + G(x)\lambda = 0 \qquad (2)$$

where H and G are jacobian matrices.

5. Data error processing. The uncertainty associated to distribution networks makes necessary to detect inconsistencies and errors in the obtained results. This stage is particularly difficult because of:

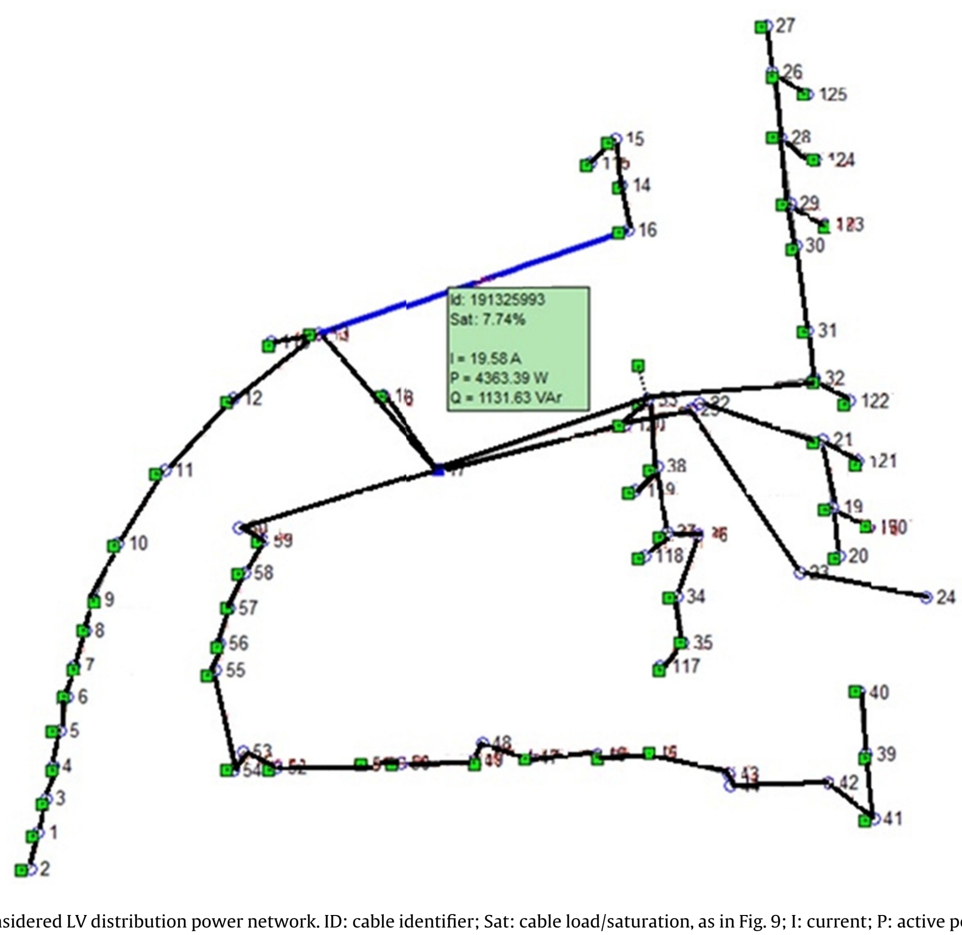

Fig. 6. Topology of the considered LV distribution power network. ID: cable identifier; Sat: cable load/saturation, as in Fig. 9; I: current; P: active power; Q: reactive power.

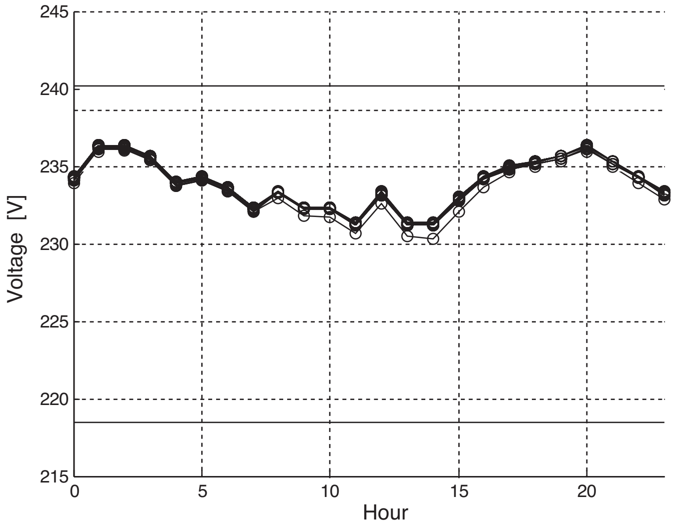

Fig. 7. Daily voltage profiles for all the buses.

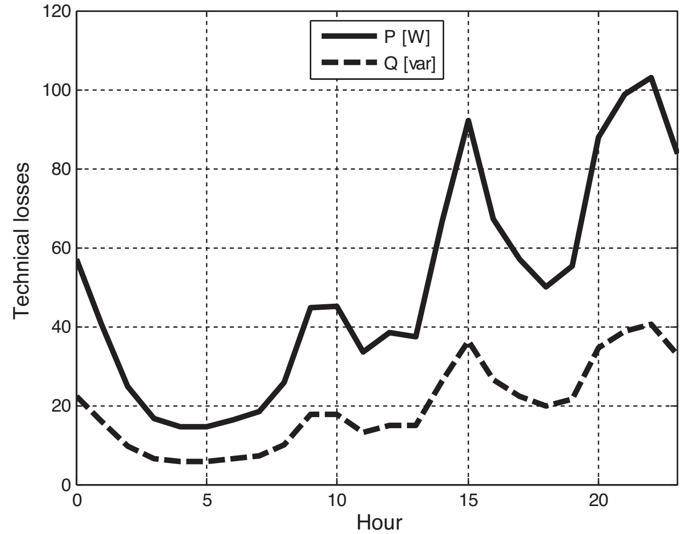

Fig. 8. Active and reactive technical losses in the network.

- Uncertainty in the network topology (e.g., topology changes, unknown line/cable parameters, etc.).
- In many cases metering data are scarce or the provided data are wrong.
- Errors associated to the location of the smart meters (e.g., inconsistencies among physical location of the smart meters in the field and location in the model).

5.2.2. Results

The architecture and the state estimation algorithm explained in Section 5.2.1 have been applied to the existing LV distribution network shown in Fig. 6, which is composed of residential and commercial customers.

Using the data provided by the available smart meters (i.e., active and reactive energy consumed/delivered by each customer), the state of the whole network has been obtained.

Fig. 7 shows the daily voltage profile for all the buses in the network. It should be noted that the voltage is kept within the allowable limits during the 24 h.

State estimation algorithm also allows computing the active and reactive technical losses in the network, as it is shown in Fig. 8. This algorithm provides information of the technical losses in each individual branch of the network, which are calculated knowing the estimated current that flows through each cable and the corresponding electrical parameters of each cable (i.e., section, resistance, and reactance). Non-technical losses are computed as the difference among the LV supervisor deployed at the SSs, smart meters' readings, estimated load demand of non-telemetered customers, and the technical losses estimated by the state estimation algorithm.

During the smart meters deployment many measurement errors were detected by the algorithm, which allowed identifying wrong physical connections. In other situations, the algorithm was not able to converge revealing that meter readings did not have the required accuracy or that their readings were anomalous (null or extremely high). Replacement of erroneous smart meters in the pilot scheme improved the convergence and accuracy of the estimations.

Thus, the most important elements of this system are the smart meters deployed at customers' premises, which provide active and reactive energy reading, and also the LV supervisor deployed at the SSs, which concentrates the information of the meters and the LV lines and sends it to upper systems. The LV supervisor provides information of mean current and voltage and mean and maximum apparent power at the SSs. In current phase of the demonstration project there was not any meter installed in the feeders sections or in the LV network and network topology was considered to be time-invariant. However, it should be noted that the accuracy of the estimated values will further improve as soon as additional measurements at LV feeders are registered.

In addition, this algorithm has already been used in the PRICE-GEN pilot scheme to detect frauds in different kind of installations (belonging to both residential and commercial customers). Initially, the algorithm evaluated the energy balance at the SS using the available measurements and the estimated values. Thus, whenever the algorithm estimated an energy balance mismatch, inspections were carried out in situ and the fraud detection was validated.

In the particular case of Spain, the Spanish Royal Decree 1048/2013 states that DSOs should reduce both their technical and non-technical losses in their power distribution networks. Consequently, the technique presented in this section will be very useful to grid operators for further reduction of losses and detection of frauds.

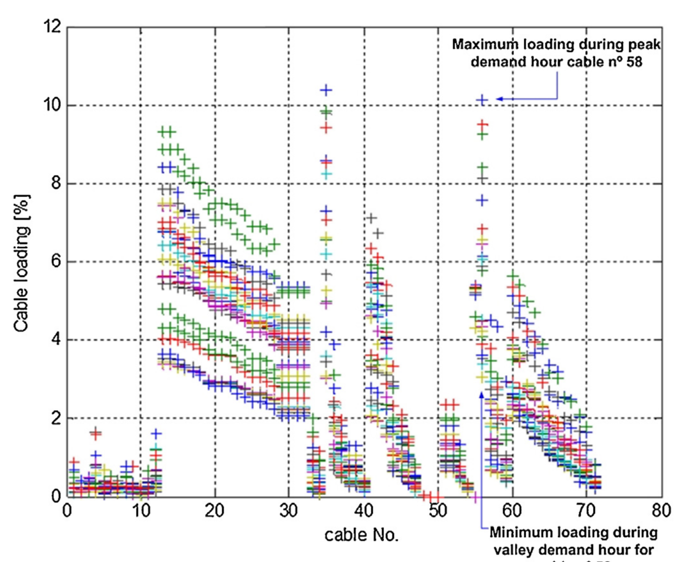

Fig. 9. Network Cable loading for 24 h operation (in %).

Finally, Fig. 9 shows the cable load[4] (in %) for each one of the branches of the considered power distribution network dur-ing the 24 h of a day. Paying attention, e.g., to cable number 58, which represents one of the worst cases, it can be seen that it reaches maximum load of almost 11% for a specific hour of the day, which corresponds to peak demand periods; whereas during valley demand periods the cable load is lower than 4%. The same tendency can be noted in the rest of the branches of the considered power distribution network. As a result, it can be concluded that the LV cables of the considered power distribution network are far away from their maximum loads even in the worst cases during peak demand periods, so they are already prepared for foreseen more challenging situations, such as increasing penetration of EVs and increasing penetration of DG.

6. Discussion

Communications architectures and technologies represent a key piece of the Smart Grid puzzle. As a result, much research has been carried out during the last years on the most appropriate commu-nications architectures and technologies depending on the specific Smart Grid application. References [44–47] address this issue for the specific case of AMI.

Reference [44] analyses the advantages and drawbacks of two communications architectures based on wireless 4G technologies (namely, LTE and WiMAX). First, direct communication between the smart meters and the MDMS is considered, focusing on the main issues that this approach presents from the communications point of view. In this regard, this paper highlights the inefficien-cies of performing connection establishment and authentication procedures in a per-smart-meter-basis and remarks upon some resultant problems that network operators would have to face in this scenario, such as the required improvement of the RAN (Radio Access Network) to avoid problems related to lack of bandwidth or coverage arising from the huge number of smart meters. To solve these problems, the paper proposes the communication through CNTRs, labeled as APs (Aggregation Points). For the communication between the smart meters and the CNTRs, wireless communica-tions such as IEEE 802.15.4/Zigbee or IEEE 802.11 are proposed. The main drawback of the latter communications architecture compared to the former one is that introducing an additional com-munications segment make it less robust against security attacks.

Despite of these problems, direct communication between the smart meters and the MDMS based on public cellular networks is winning momentum in some countries, such as the UK (United Kingdom). In addition, [45] proposes deploying an entirely new cel-lular network based on CDMA-450 (Code Division Multiple Access at 450 MHz) exclusively devoted to the Smart Grid applications pro-vided by a given DSO. Within this approach, the DSO would be the owner of the communications infrastructure, but a telecom opera-tor would be responsible for running it. The paper claims that this is a suitable solution from both technical and economic perspectives for the specific boundary conditions of the Netherlands. However, this would not be the case in other countries where the license to operate in this frequency band is too expensive or where this frequency band is already allocated for any other use.

There are also proposals of using wireless mesh networks as last mile solutions [46], which shows fairly high adoption in areas such as California (USA). This approach presents advantages from the point of view of the management and maintenance of the infra-structure, although it may also present higher security risks.

[4] Cable load is defined as the ratio between the hourly cable load and the nominal current of the cable.

Regarding hybrid architectures which combine wireless and wired technologies, PLC seems to be the most promising last mile technology for AMI applications [47], due to the reasons that have been disclosed throughout this paper. Reference [48] presents an updated overview of the deployment of PLC for AMI applications by European utilities, pointing out that NB-PLC technologies are the leader in the last mile. The paper covers the most relevant NB-PLC technologies, namely:

- Meters & More, which is promoted by the Enel Group. Its lower layers are being standardized by the IEC. Meters & More is being widely deployed in those countries where the Enel Group presents high market share (e.g., Italy).
- OSGP (Open Smart Grid Protocol), which is promoted by Eche-lon. Its lower layers are being also standardized by the IEC. OSGP presents its highest penetration rates in the Nordic countries.
- G3, which is promoted by EDF and Maxim. Its PHY and MAC layers have already been published as standard by the ITU-T [49]. G3 shows the highest penetration rates in those countries where EDF presents high market share (e.g., France).
- PRIME, which is promoted by the PRIME Alliance, led by Iberdrola. Its PHY and MAC layers have been also published as standard by the ITU-T [16]. PRIME is being widely deployed in Spain, as it is shown throughout this paper, and also in other countries like Portugal, UK, Poland, Brazil, USA, or Australia.

All these NB-PLC technologies use DLMS/COSEM at the appli-cation layer. There are standardization efforts to try to harmonize them, such as the ITU-T G.HNEM [50]. One of the main problems that have been detected in the pilot regarding NB-PLC communica-tions has to do with EMI (Electro Magnetic Interference), which sometimes make the behavior of the communications network unpredictable. As matter of fact, the main standardization bod-ies are aware of this and they are working to try to mitigate this problem [51].

In truth and in fact, the matter of the most appropriate commu-nications architecture and technologies eventually depends on the specific business case behind the target application, which in turn depends on many factors, such as the special features of the target application itself or the special features and the specific regula-tion of each country (which varies, e.g., even among EU countries). As a result, simulations represent a key tool to evaluate different options before undertaking the important investments needed to deploy this kind of infrastructures on a large scale. The research in this area can be classified depending on where it is focused. Thus, some research efforts are mainly focused on evaluating the perfor-mance of the lower layers of the communications protocols [52]. There are also research works focused on evaluating some figures of merit of the communications infrastructures themselves [53], as it is also the case of the simulations outlined in Section 5.1. Finally, as the Smart Grid brings energy and ICT together, much research has been conducted on co-simulation of energy and ICT infrastruc-tures [54–59], which represent a very promising and challenging research area.

Regarding the impact on the communications infrastructure of a centralized architecture compared to a fully distributed one,[60] evaluates this issue focusing on scalability as figure-of-merit of the system and using the deployment costs and the so-called ABDP (Accumulated Bandwidth-Distance Product) as metrics. The main conclusion of this work is that simulations show that a dis-tributed architecture brings more benefits to the communications infrastructure than a centralized one. This is also the approach of agent-based solutions such as the one presented in [61]. However, the market trend does not seem to be in line with distributing the data processing throughout the communications infrastruc-ture, but to do it at the same logical entity applying cloud computing and Big Data. Thus, Big Data techniques, such as MapReduce [62,63], which facilitate handling the huge volume of data generated by AMI in a short period of time by allowing processing them in parallel using a cluster composed of several machines (i.e., taking advantage of the cloud computing paradigm), are crucial in these novel scenarios.

7. Conclusions

This paper discusses the state of the art and current main technological trends in AMI from the ICT perspective.

In particular, the paper is focused on the M2M communications architecture and technologies deployed in the large-scale AMI pilot scheme of the Spanish R&D demonstration project PRICE-GEN, which is integrated into an operational power distribution network. The pilot scheme itself is also described in detail, paying special attention to how it is currently operated (e.g., tests that are carried out, services that are delivered) and to the next steps. This pilot scheme will be also used in the EU R&D project IGREENGrid [64].

One of the main impacts of this paper is that it can be taken as reference when making such a key decision as which communications architecture and technologies to use in large-scale AMI deployments. Although in truth and in fact there is no single answer to this question, since this eventually depends on many factors, such as the special features and constraints of the underlying power infrastructure or the special features and the specific regulation of each country, the methodology and analysis conducted in this paper can be applied in general, and the specific M2M communica-tions architecture and technologies proposed in this paper are valid for countries where such boundary conditions are similar to Spain.

Acknowledgments

This work has been partly funded by the Spanish Ministry of Economy and Competitiveness through the INNPACTO Programme under the project PRICE-GEN (IPT-2011-1507-920000).

The authors would like to thank the support and collaboration of all the partners of the PRICE-GEN consortium: Arteche, Centro de Investigación de Recursos y Consumos Energéticos, Current Iberia, Iberdrola Distribución, Universidad Carlos III de Madrid, Unión Fenosa Distribución, and ZIV Metering Solutions.

The authors would also like to thank the anonymous reviewers for their valuable contribution and constructive feedback.

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